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Dynamic modelling for ecological and economic sustainability in a rapid urbanizing region

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Abstract

Recently years, most of China’s rapidly developed regions are becoming China's large industrial cities and drawing the attention of the world. Consequently, the impacts of rapid urbanization to urban ecosystem will be greatly increased with the increasing economic development. If relationship between economic development and ecological sustainability is not fully realized, urban ecosystem will be degraded at a high rate. Therefore, study on ecological and economic sustainability for this area is of great importance. The objectives of this study are: (1) to find a balance between economic development and ecological protection in these regions; (2) to develop a process-based ecological and economic sustainable development model; (3) to supply the optimal controls for these reigns by conducting a policy analysis. To this end, a system dynamic model for urban sustainable development was constructed. The model was based on the analysis of many index and three subsystems, which are society system, economic system, and environmental system. We also selected typical development policies for a rapidly urbanizing region, Tianjin, in the future.

*Keywords:*Tianjin; system dynamic simulation; ecological and economic sustainability

1. Introduction

Since economy in China has been developing with a rapid growth rate recently, which lead to region urbanization also increase with an alarming rate. These regions particularly distribute in the area around

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urban that have relative good eco-environment condition. As a result, the Chinese government has dramatically increased its monetary investments in region economic development planning and infrastructure construction, especially around Bohai Sea. However, the economic construction may be too rapid to better considering local environment. That results in severe ecological problems and environment pollution. Such problem is an important factor restricting sustainable development in the field of region economic and environment. What is more, before implementing a region economic development planning, it is a crucial step to predict the ecological impacts in environmental assessment.

How to satisfy the huge demand for economic growth whilst maintaining adequate sustainability and protection of the region of ecological interests is a major challenge for all planners in China and whole world [1]. Sustainable region development is a notion that come from the report Limits to Growth [2].
Many scholars have examined the issues of sustainable region development from different perspectives with various policy implications. Tang, Tang, and Roger [3] assessed the effectiveness of a new system analysis method in Hong Kong to find out the ways for balancing urbanization and sustainable development. Hersh [4] was interested in the modelling and measurement of sustainable development, from the perspective of systems methodologies.

The research on evaluation sustainable development increased dramatically, and important approach, such as system dynamics (SD) emerged. SD, which was introduced by Jay Forrester in the 1960s [5] provides effective methodology for better understanding large-scale and complex management problems [6].

SD is a system dynamics methodology, an effective approach in dealing with dynamic problems [7, 8]. Understanding of how the existing processes, information and management interact in creating the dynamics of the variables of interest is the point of system dynamics methodology. These factors and the relationships between them constitute the framework of the system. It is necessary in system dynamics method that model should provide a valid explanation of the actual system [9, 10]. The aim of a system dynamics study is to show how and why the problem is generated and to find points in the system that would be effective in eliminating the factors resulting problem. These points are then applied to make policies to improve the state of affairs. SD has been used in many areas including social and economic analysis [11], agricultural systems [12], natural resource management [13], and sustainable development [14-16].

The objectives of this study are: (1) to develop a process-based rapidly urbanizing region model; (2) to test the robustness of the newly built model in simulating dynamics in ecological sustainability and economic growth in a rapidly urbanizing region, Tianjin; (3) to examine the optimal controls of parameters and environmental factors for this model by conducting a sensitivity analysis; and (4) to apply the model to evaluate the effects of some policies on the ecological and economic dynamics in Tianjin, a rapidly urbanizing region in China.

2. Materials and methods

2.1. Study region

As a major of Chinese rapidly urbanizing regions, Tianjin is the center for Bohai Economic Rim, an emerging economic development area. It is becoming one of the Northern economic powerhouses, rivaling the Pearl River Delta in the south and Yangtze River Delta in the east and drawing the attention of the world. Consequently, the impacts of increased urbanization and human disturbance to ecosystem will be greatly increased.

Fig.1. Location of Tianjin City in China

Tianjin (38°34′N-40°15′N and 116°43′E-118°194′E) is located in the Northeastern China, and bounded to the east by the Bohai Bay (Fig.1). It is a metropolis with area of approximately 11,760 km^2 and one of the five national central cities [17]. Climatic conditions are characterized by a temperate, continental monsoon climate, distinct seasons, and contemporary conditions for rain and heat. The average annual air temperature is 12.6°C, and total evaporation is about 1750~1840mm, total precipitation is about 500~600 mm, most of which falls between June and August. It is border Beijing Municipality, and the population of Tianjin ranks sixth in the People's Republic of China. At the end of 2010, the population of the Tianjin Municipality was 12.94 million and Tianjin's gross domestic product (GDP) was 140.9 billion US$(910.8 billion RMB). Tianjin is known as one of China's developed cities is the center of Northern China and an emerging economic development region with rapid economic growth in recent years.

2.2. Model description

The main elements of a system dynamics model are stock variables, flow variables and auxiliary variables. Stock variables are also known as level variables,which represent major associations in the system. Flows variable (also known as rates) were symbolised by valves. A flow diagram was established by incorporating the various features related to the wetland management. The flow diagram was also present the association between each element in the diagram. Dynamics of the model are determined by the feedback loops of the diagram. Each arrow in the diagram indicates the influence of one element on the other. The influence is considered negative (-) if a decrease in one element causes an increase in another or positive (+) in the opposite case.

2.3. Data

Data for the model simulation included society conditions, economic conditions, and environment conditions. The data of eco-environmental indicators are originally from China Environment Yearbook (1990-2008). The other data are obtained in Tianjin Statistical Yearbook (1990-2008). We used software package Vensim (version 5.9) for system dynamics analysis.

3. Results

3.1. Assumptions and model structure

For better understanding the model, the major assumptions should be mentioned at first as follows:

• Rapidly urbanizing process is a dynamic system process, and rapidly urbanizing problems are system problems.

• The whole system can be studied with three major sectors: society sector, economic sector, and environment sector.

• These sectors contact with each other by some factors.

• The deep inner micromechanism among factors is ignored in the model.

• For the study focus on human activity, the effect of changes by normal nature power on system in short-term is assumed negligible.

• Random effects are ignored in the model because of the lack of available data and because randomness is unlikely to change the major behaviour patterns significantly. Therefore, average values are assigned to all parameters and inputs.

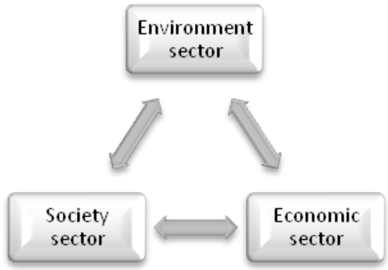

Fig.2. Model structure with the sectors

The three major sectors of model that can be mentioned as: society sector, economic sector and environment sector on the region system (Fig. 2). Each consists of several sub-sectors.

3.2. Model development

3.2.1 Society sector

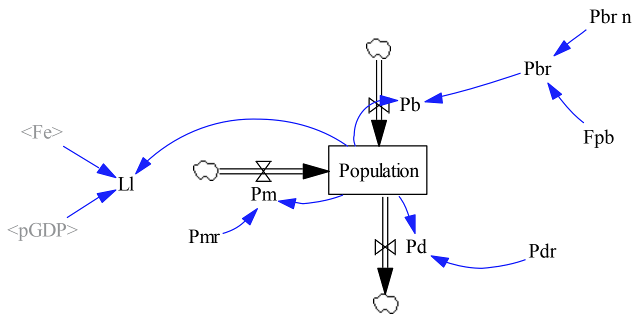

Fig.3. Diagram of the society sector

In society sector, the Population (total population) was taken as the level variables. Average annual newly-born population (Pb), average annual death population (Pd), average annual emigrant population (Pm) were taken as flow variables. The influence of family planning policy on society sector depended on fertility impact factor (Fpb). Auxiliary variables include birth rate (Pbr), mortality rate (Pdr), population migration rate (Pmr), natural birth rate (Pbr n), and livability (Ll). The main equations of society sector are as follows:

$$\mathrm{L}\ Population_T = population_{T\text{-}1} + Pm + Pb - Pd \tag{1}$$

$$\mathrm{R}\ Pm = Population \times Pmr \tag{2}$$

$$\mathrm{R}\ Pb = Population \times Pbr \tag{3}$$

$$\mathrm{R}\ Pd = Population \times Pdr \tag{4}$$

$$\mathrm{A}\ Pbr = Pbrn + Fpb \tag{5}$$

$$\mathrm{A}\ Ll = \mathrm{Function}\ (Population, Fe, pGDP) \tag{6}$$

The population (Population) in Tianjin is increasing. There is an increase of average annual emigrant population (Pm) in Tianjin city, which is expected because the economy grows rapidly. Birth rate (Pbr)is higher than mortality rate (Pdr), so that is another reason to drive population increase. Attractiveness of all three main effects for population, natural birth rate (Pbr n) and fertility impact factor (Fpb) in the region is nearly small change this years. Thus, the main factor that control population increase is immigration. Likewise, population is also play an important role in region livability (Ll). Consequently, it is observed that there is an increase in the total population and a decline in region livability (Ll), especially after the year 2000, when the permanent population is more than 10 million persons. This is the most notable dynamics in this sector.

3.2.2 Economic sector

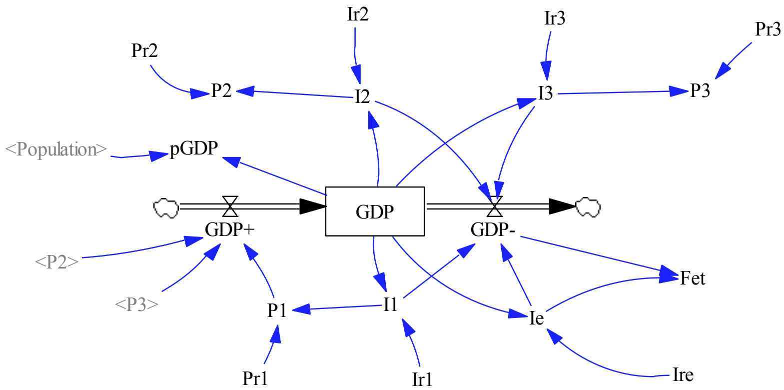

Fig.4. Diagram of the economic sector

Economic sector is the center for the whole dynamic system, which establishes ecological industry chain and net through industries to achieve material circulation, energy utilization and wastes recycling. The economic sector is shown in Figure 4. We took primary industry subsystem, secondary industry subsystem and tertiary-industry subsystem into consideration to simplify the system dynamic model.

The GDP (gross domestic production) was taken as level variables, gross domestic production increase (GDP+) and gross domestic production decrease (GDP-) were taken as flow variables. Auxiliary variables include investment in primary industry (I1), investment in secondary industry (I2), investment in tertiary-industry (I3), investment in environmental protection (Ie), agricultural production value (P1), industrial production value (P2), tertiary-industry production value (P3), investment rate of primary industry (Ir1), investment rate of secondary industry (Ir2), investment rate of tertiary-industry (Ir3), investment rate of environmental protection (Ire), rate of return for primary industry investment (Pr1), rate of return for secondary industry investment (Pr2), rate of return for tertiary-industry investment (Pr3), scientific and technological factors for environment protecion (Fet). The main equations of society sector are as follows:

$$\mathrm{L}\ GDP = (GDP+) - (GDP-) \tag{7}$$

$$\mathrm{R}\ (GDP+) = P1 + P2 + P3 \tag{8}$$

$$\mathrm{R}\ (GDP-) = I1 + I2 + I3 + Ie \tag{9}$$

$$\mathrm{A}\ P1 = I1 \mathrm{x} Pr1 \tag{10}$$

$$\mathrm{A}\ P2 = I2 \mathrm{x} Pr2 \tag{11}$$

$$\mathrm{A}\ P3 = I3 \mathrm{x} Pr3 \tag{12}$$

A $I1 = GDP x Ir1$ (13)

A $I2 = GDP x Ir2$ (14)

A $I3 = GDP x Ir3$ (15)

A $Ie = GDP x Ire$ (16)

A Fet = Function $((GDP-), Ie)$ (17)

A $pGDP = GDP / Population$ (18)

In the model used in this study, the economy subsystem is based on the Gross Domestic Product (GDP). According to the theory described by the production function, the GDP of each sector in each industry can be determined based on the invested capital. This information then allows the GDP expenditure to be calculated. Fig. 3 depicts the economy subsystem model used in this study.

3.2.3 Environment sector

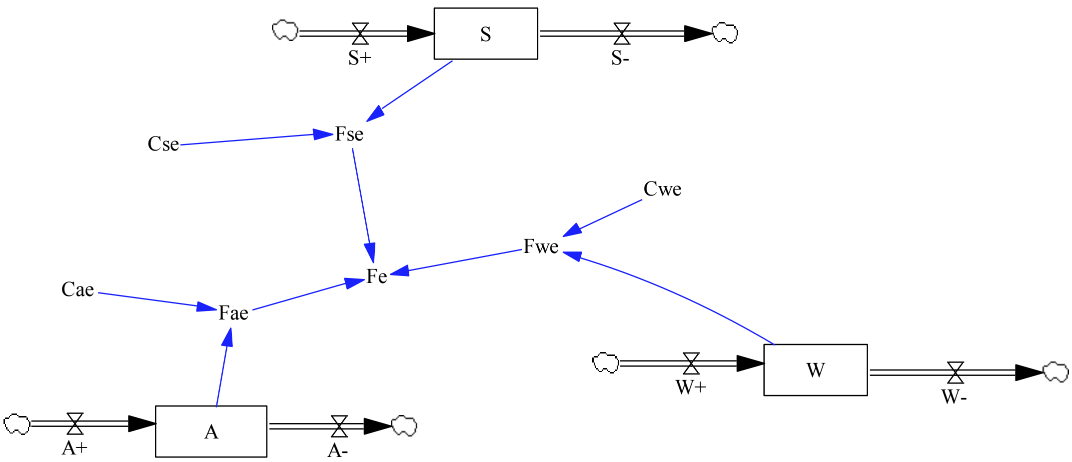

Fig.5. Diagram of the environment sector

The environment sector was established based on three issues, the atmosphere pollutant subsystem, solid waste subsystem and waste water subsystem. Therefore, atmosphere waste, solid waste, and waste water discharge were taken as level variables. A+ (atmosphere pollutants increase), S+ (solid waste increase), W+ (waste water increase), A -(atmosphere pollutants decrease), S- (solid waste decrease), and W- (waste water decrease) were taken as flow variables in each subsystem. Auxiliary variables include atmospheric environmental condition factor (Fae), atmospheric environmental capacity (Cae), water environmental condition factor (Fwe), soil environmental condition factor (Fse),soil environment capacity (Cse), water environment capacity (Cwe). The main equations of society sector are as follows:

L $A = (A+) - (A-)$ (19)

L $W = (W+) - (W-)$ (20)

L $S = (S+) - (S-)$ (21)

A $Fae = A / Cae$ (22)

A $Fwe = W / Cwe$ (23)

$$A\ Fse = S / Cse \tag{24}$$

$$A\ Fe = Fae + Fwe + Fse \tag{25}$$

3.3. Policy analysis

Human requirements and activities determine ecological sustainability [18], while rapidly urbanizing region is one of impact factors on key underlying environment gradients [19]. Therefore, rational region development can optimize ecological and economic sustainability. The study on ecosystem to region development transformation has facilitated planners to consider ecological region development into general region development planning. The local government has paid more attention to ecological damage and environment restoration.

This study supplied the administration department with a new view for sustainability management. Rich and balanceable ecosystem services can maintain the Earth's life support system. The response of ecosystem to the whole process of region development transformation reflects ecological activity. Obviously, it includes two types, positive and negative. Only the total quantitative balance for compensating negative ecosystem cannot sustain an even development in all regions. The extreme region development distribution can widen the ecological or economic risk, and restrict the sustainable development.

The study results enable the reasonable reallocation of resources to achieve the overall economic and ecological goal, including the adjustment of quantity, quality, spatial distribution and match types. Various signs indicate that region development footprint aggravates ecological loss and deterioration. Examination of the spatial relationships between ecological sustainability and distribution can reveal the interest and conflict for sustainable development. To be sustainable, humanity must live within nature's carrying capacity [20]. Overload causes an accelerated deterioration, which lowers regional ecological sustainability.

The future region development should be targeted at production efficiency, unit GDP energy consumption, clear production and cyclic economy, and local government should also largen the proportion of non- pollution industries. In industrial areas, ecosystems are eroded by a combination of natural and human behaviors [21]. And ecosystems exposed to undue industrial disruption are more difficult for maintenance [22]. Functional grading and zoning of region development can direct future region development [23, 24]. Hence, the ecosystem indices and mapping of ecological sustainability proposes the target of environment management, listed as the following two aspects.

On the one hand, the areas with low ecological sustainability should be focused on ecological restoration and improvement, and local government should arrange region development and increase ecological investment to make the deterioration under human control; on the other hand, the areas with high ecological sustainability should be focused on prevention and protection, and local government should develop various types of land under the guarantee of necessary ecological land. The key point must be paid more attention to "balance" between economy and ecology, represented by region development and ecosystems. For region development/ecological planners, the environmental actions should do their efforts on weakening negative region development transformation, increasing ecosystem types in a definite area as possible and balancing region development for different purposes.

4. Conclusions

In this study, a system dynamics model that comprises an integrated environmental-social- economic system is developed to assist evaluation of the possible impacts of government policies on sustainable development. The model examines interactions among three sub-systems within a rapidly urbanizing region, Tianjin in China. Furthermore, some policy suggestions are proposed through the observations from the model, which is actually the ultimate goal of most system dynamics models.

The conclusion is that only by means of a planning policy scheme to support compact and high-density development could rapidly urbanizing region meet the environmental, social and economical requirements of sustainable development and achieve a perfect balance among them. The modeling results are directly useful to planners and policy makers by comparing different dynamic consequences brought by various policies and decisions. It is useful in answering questions such as ‘‘how a rapidly urbanizing region can be developed under ecological and economic sustainability’’

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